

# Modeling the inner zone protons

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## CRAND (cosmic ray albedo neutron decay)

model of proton intensity  $j$  balances the neutron decay source strength  $S_n$  and the energy loss rate  $dE/dt$ :

$$\frac{\partial}{\partial t} \left( \frac{j}{v} \right) + \frac{\partial}{\partial E} \left( \frac{dE}{dt} \frac{j}{v} \right) = S_n$$

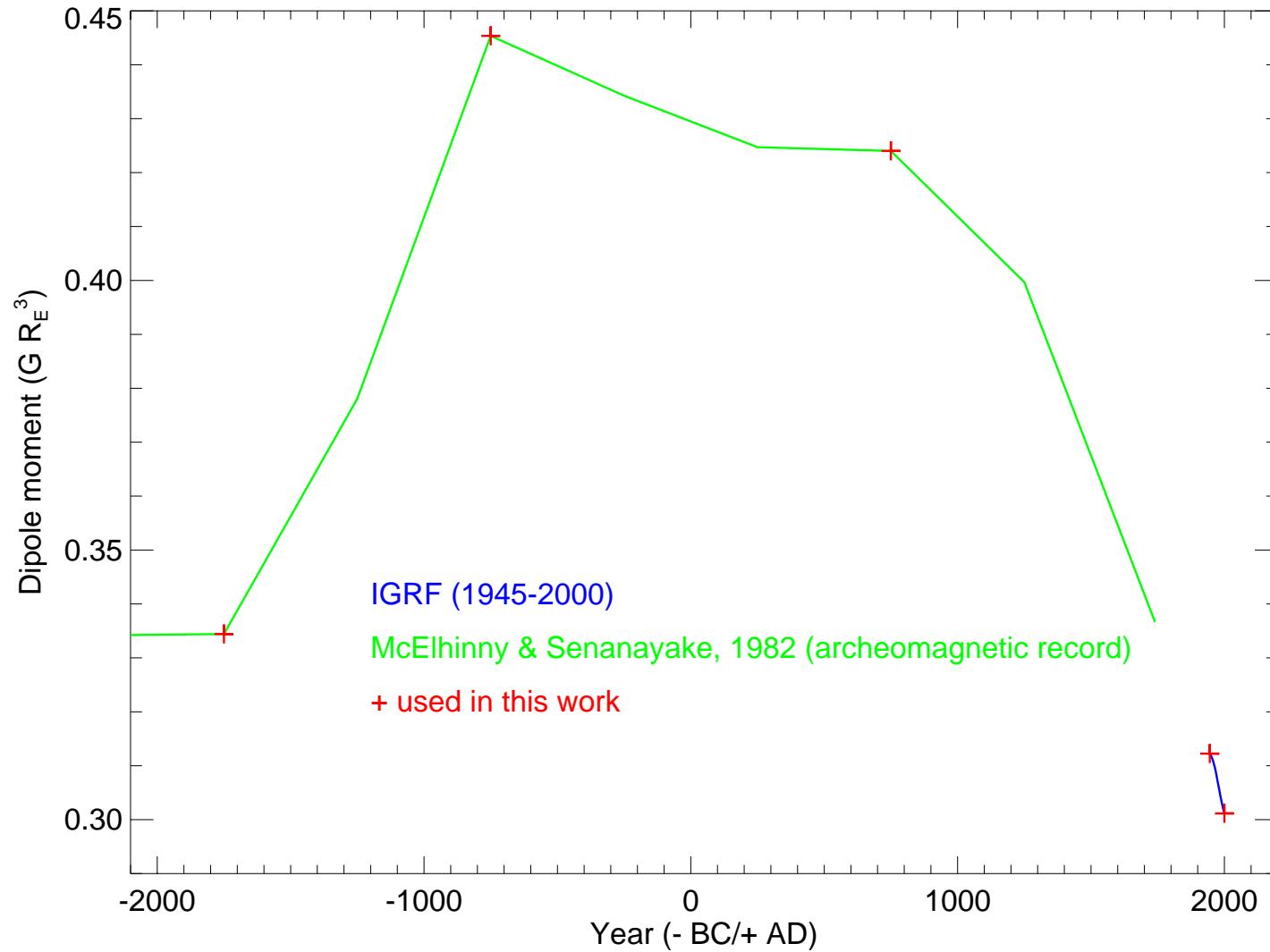
the solution is:

$$j(E, t) = v(E) \int_{t_0}^t S_n(E', t') e^{- \int_{t'}^t C(E'', t'') dt''} dt' \quad \text{where } C = \frac{\partial}{\partial E} \left( \frac{dE}{dt} \right)$$

Steps in calculation:

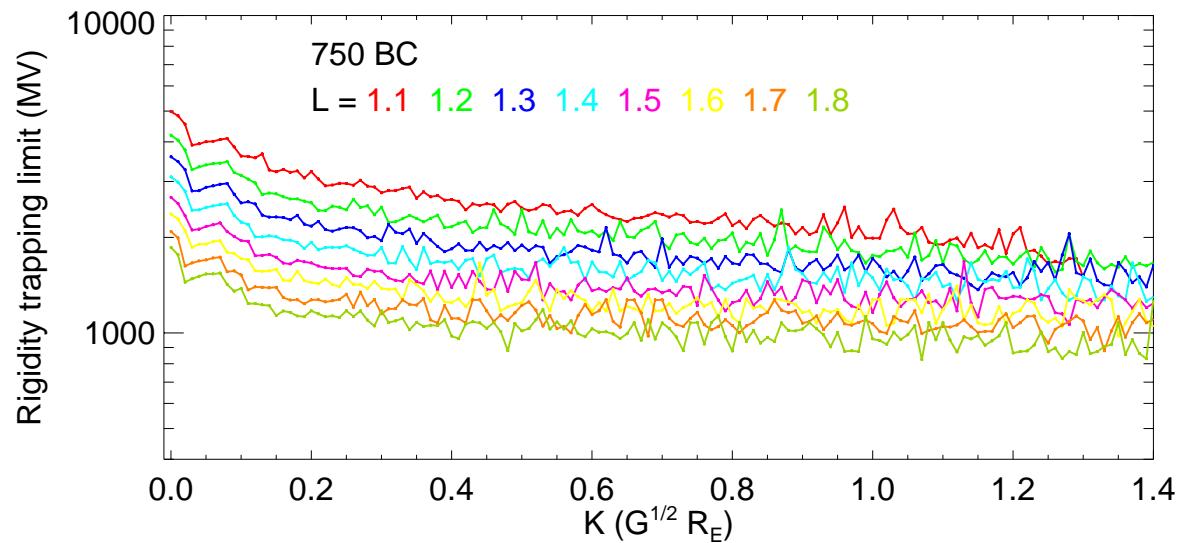
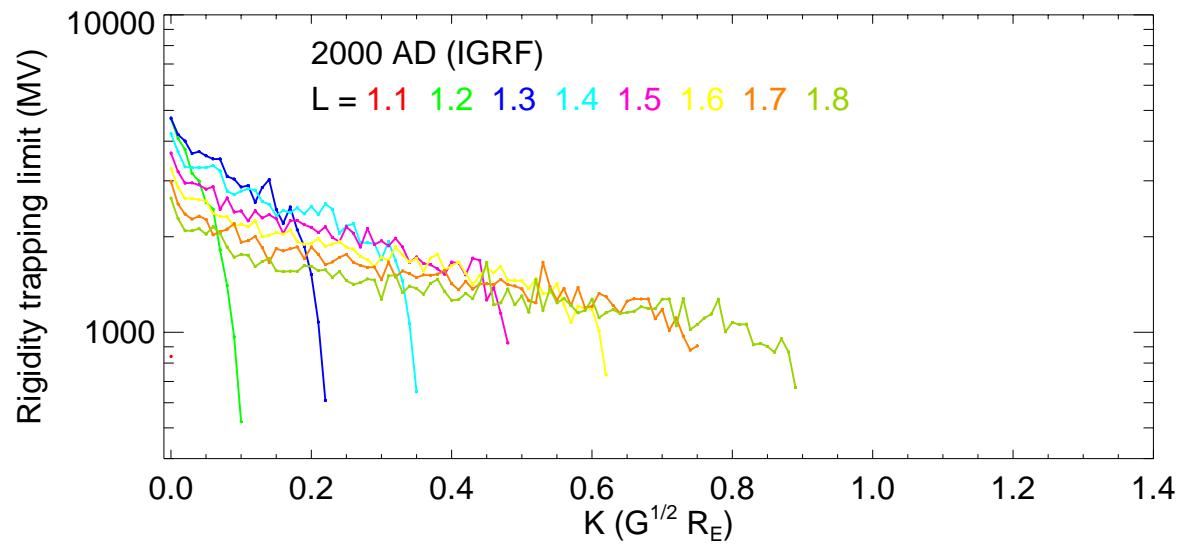
1. Pick a time dependent geomagnetic field model
2. Find proton trapping limits
3. Get neutron albedo flux from galactic cosmic ray (GCR) spectrum and model atmosphere
4. Drift average neutron decay source and atmosphere/ionosphere/plasmasphere densities
5. Get trapped proton distribution by numerical integration

## 1. Geomagnetic field model



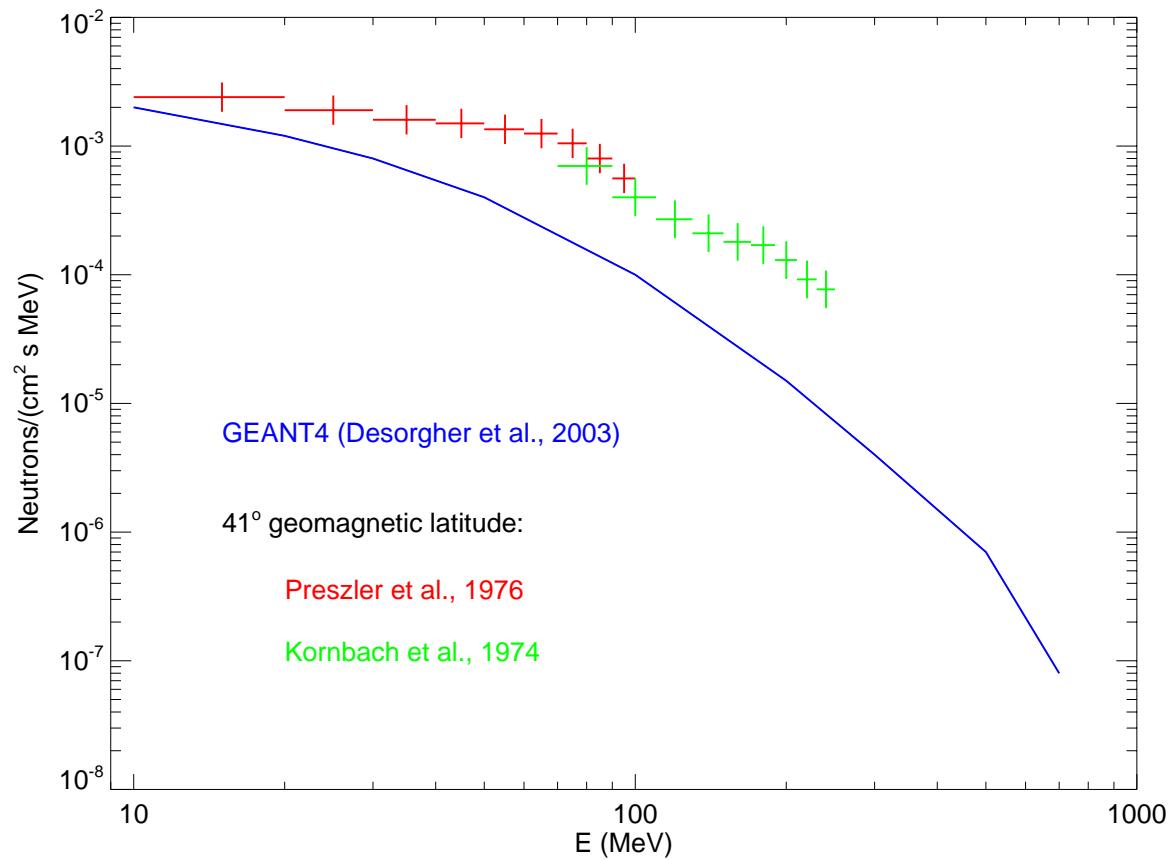
## 2. Proton trapping limits

by numerically tracing particle trajectories:



### 3. Neutron albedo

Use GEANT4 Monte Carlo simulation of GCR spectrum and MSIS model atmosphere



## 4. Drift averaging

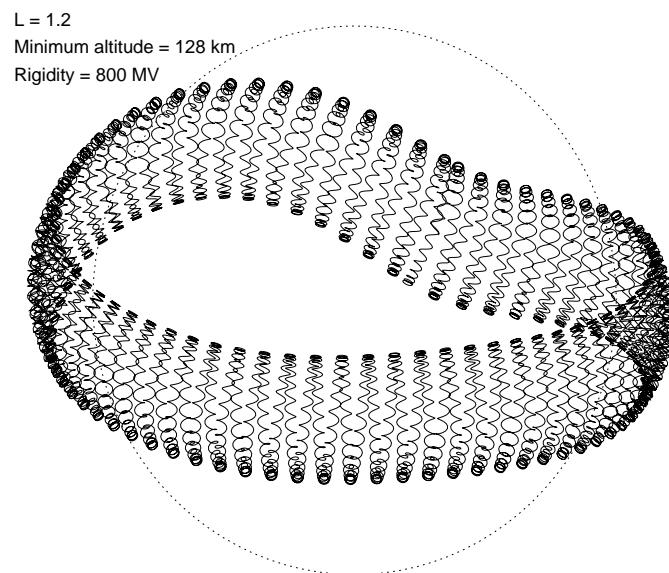
by numerical integration along spiral path for each M, K, L, and  $F_{10.7}$ :

$$S_n = \frac{\langle j_n \rangle}{v\gamma\tau}$$

$\tau$  = neutron mean lifetime, 887 s.

$$\frac{dE}{dt} = \sum_i \langle n_i \rangle v \frac{dE}{d\bar{x}_i}$$

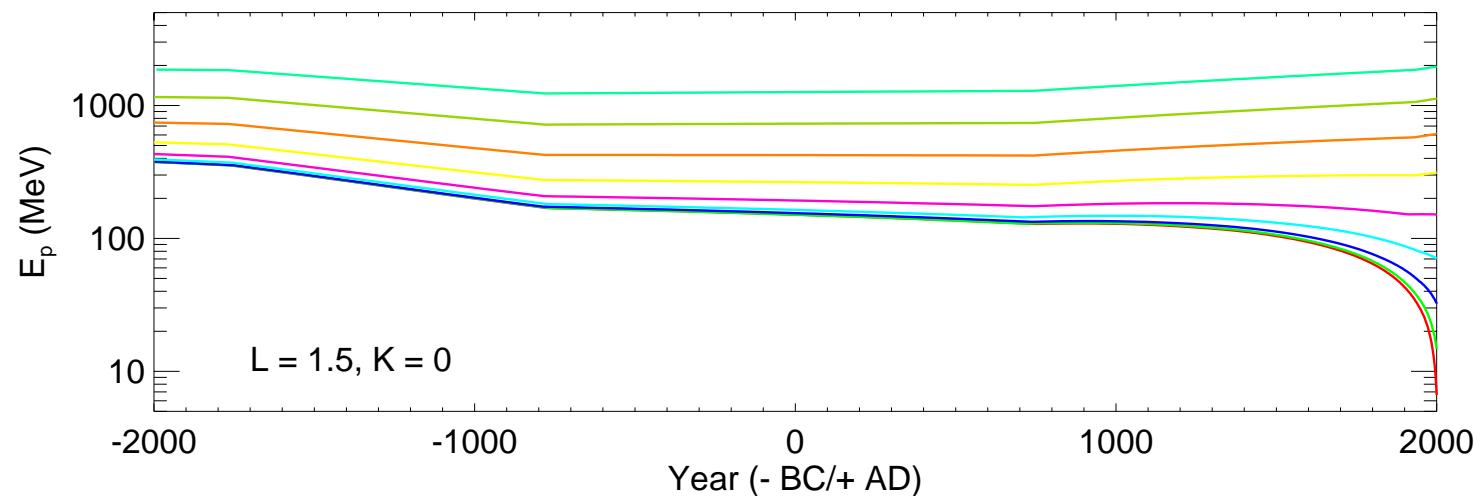
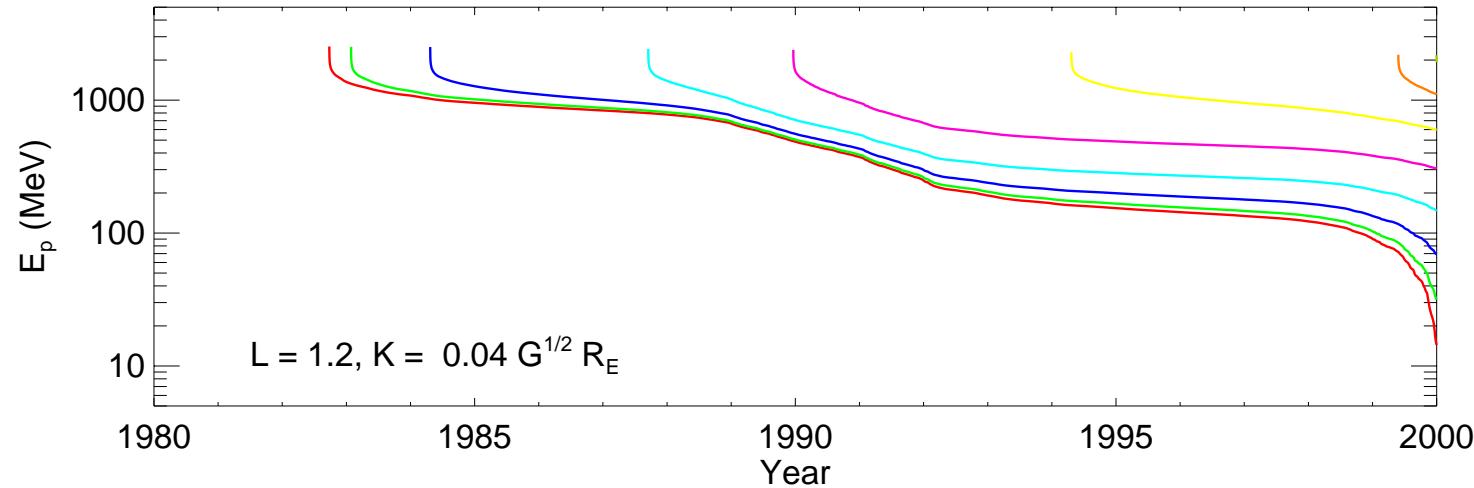
neutral H, He, O, O<sub>2</sub>, N, N<sub>2</sub>, Ar,  
and iono/plasmaspheric  
free electrons.



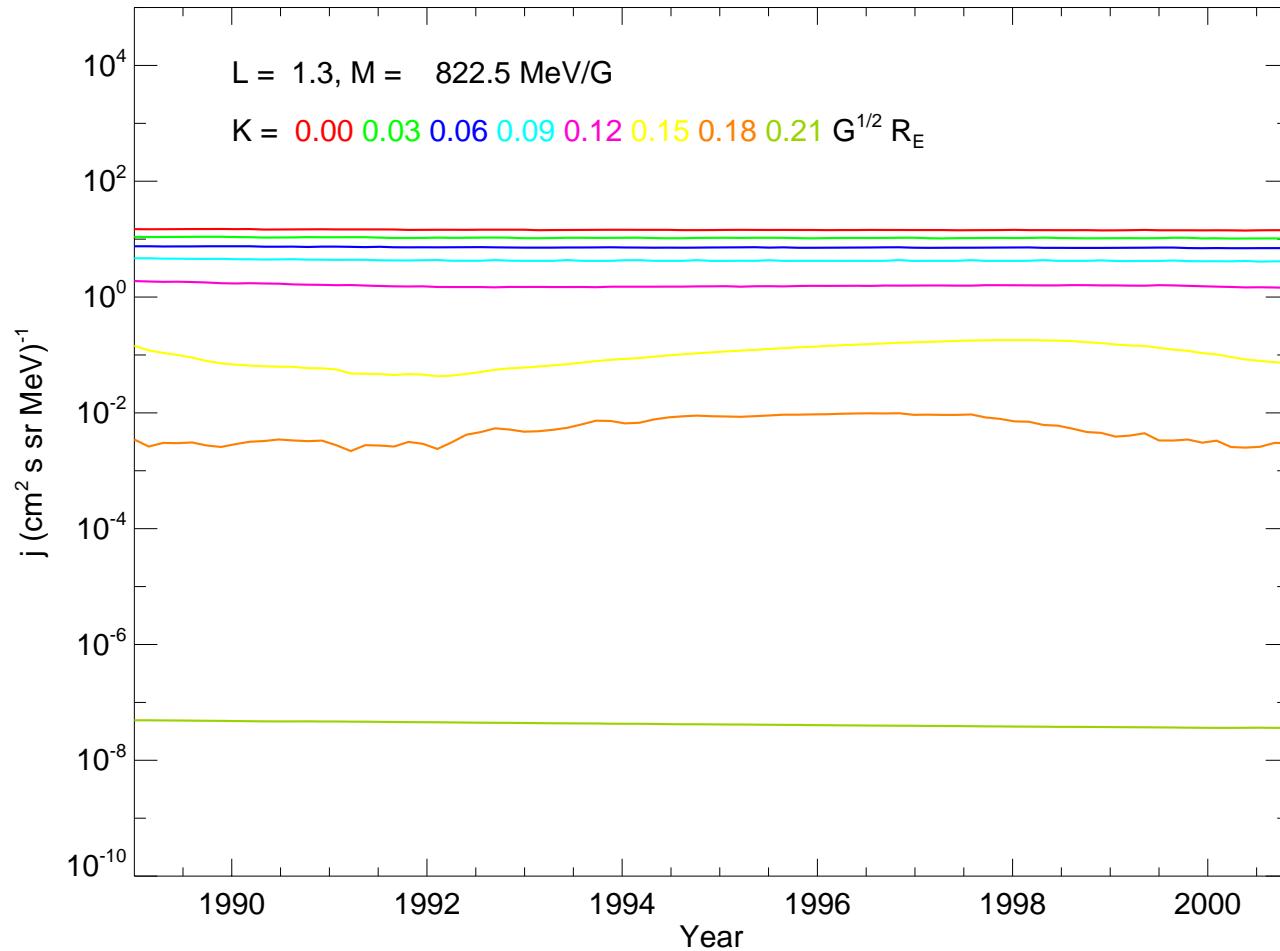
## 5. Numerical integration

over proton residence times.

Varying timescales for proton energy gain/loss:

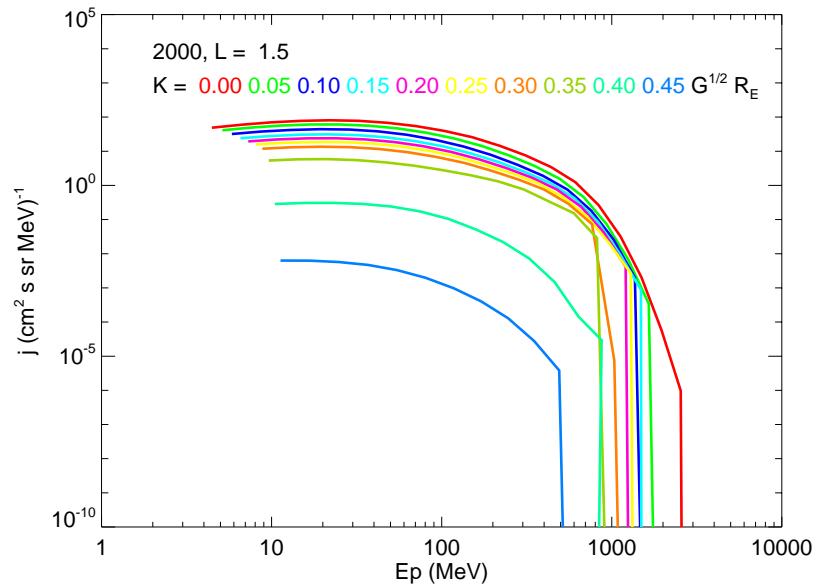
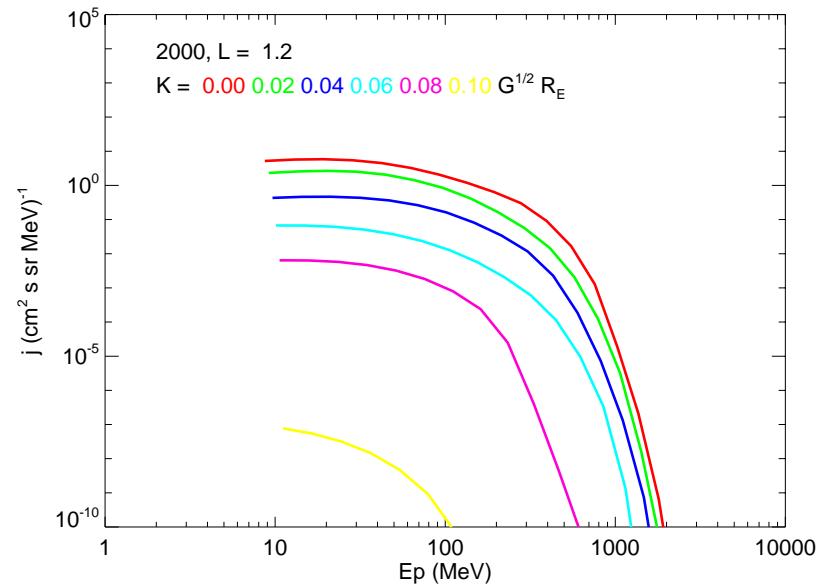


## Trapped proton intensity

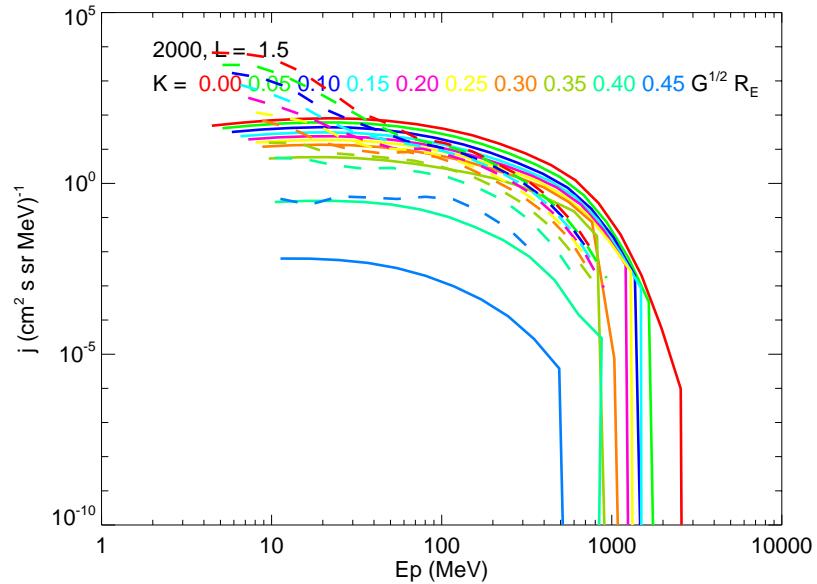
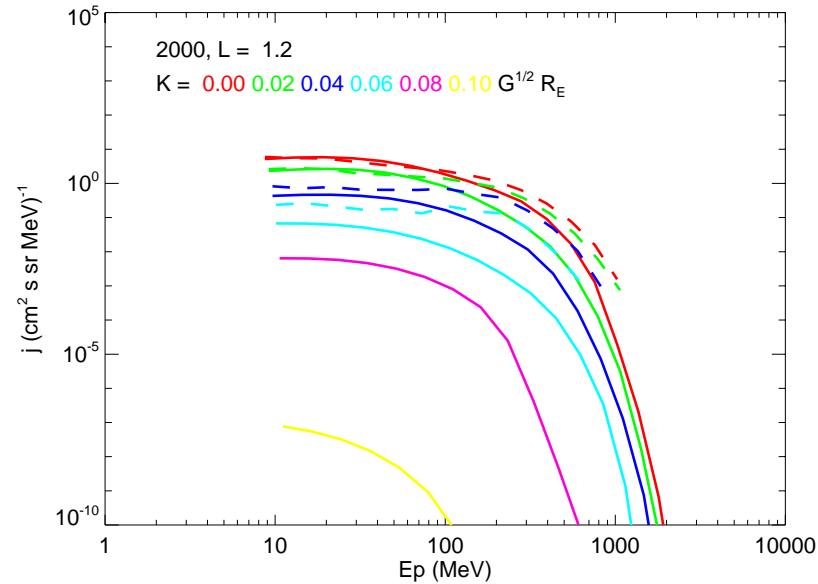


Solar cycle dependence is apparent for timescales  $\lesssim 10$  years  
and mirror point altitudes with varying atmospheric density.

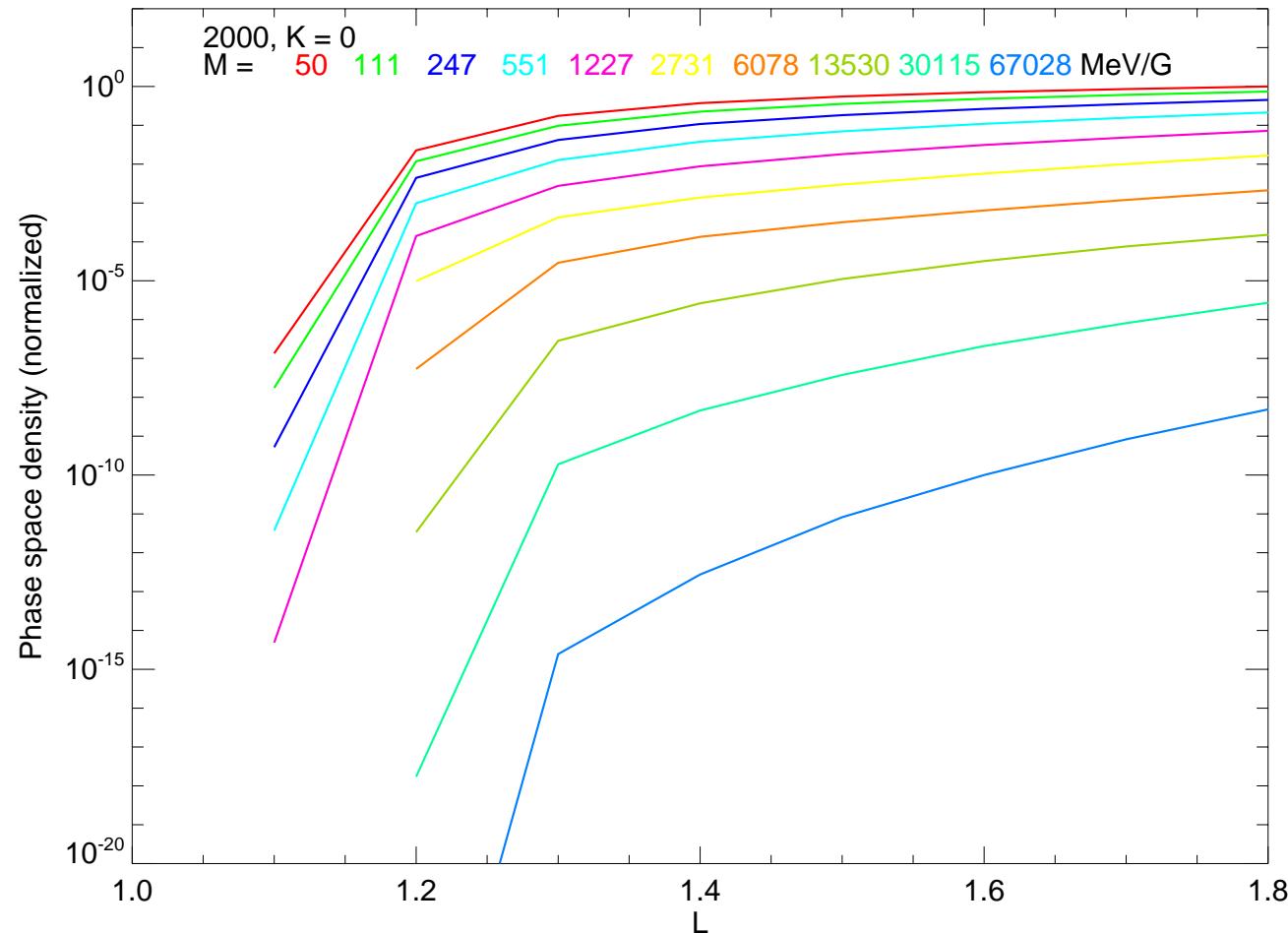
## Proton energy spectra



## Compare spectra with AP8



## Phase space density profiles for radial diffusion



## Conclusions

- Improvements on earlier models:
  - Time varying geomagnetic field
  - Rigidity dependent drift averaging
  - Simulation of neutron albedo (GEANT4)
  - New models of atmosphere/ionosphere (MSIS/IRI)
- For high energy protons near trapping limit  
need geomagnetic field models for last  $\sim$ 3000 years
- For lower energies ( $< 100$  MeV), last  $\sim$ 300 years is sufficient,  
but radial diffusion is also needed

## Future improvements

- Neutron albedo including GCR temporal and spatial dependence
- Nuclear interactions (?)
- Inward radial diffusion of solar protons (?)